In situ local shock speed and transit shock speed

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Abstract. A useful index for estimating the transit speeds was derived by analyzing interplanetary shock observations. This index is the ratio of the in situ local shock speed and the transit speed; it is 0.6–0.9 for most observed shocks. The local shock speed and the transit speed calculated for the results of the magnetohydrodynamic simulation show good agreement with the observations. The relation expressed by the index is well explained by a simplified propagation model assuming a blast wave. For several shocks the ratio is approximately 1.2, implying that these shocks accelerated during propagation in slow-speed solar wind. This ratio is similar to that for the background solar wind acceleration.

Keywords. Interplanetary physics (Flare and stream dynamics; Interplanetary shocks; Solar wind plasma)

1 Introduction

Interplanetary shock propagation has been studied. Dryer (1974 and references therein) reviewed the observational and theoretical approaches to explaining those shock waves. Pinter (1982 and references therein) reviewed the general properties of those shocks based on observations.

The Mariner 2 spacecraft recorded an interplanetary shock on 7 October 1962 (Sonnet *et al.*, 1964), the first direct observation of an interplanetary shock. The sudden commencement (SC) of a geomagnetic storm was recorded in association with this shock. Gosling *et al.* (1968) noted that the speed of the shocks observed by the twin Vela 3 satellites was significantly less than the transit speed of the shock from the Sun to Earth. Hundhausen (1970) calculated the transit speed by using the timing between the eruptive flare and the SC for the shocks between 1962 and 1967. Comparing the in situ speed with the transit speed indicated that most shocks decelerated during transit.

Chao and Lepping (1974) compared the transit speed with the *in situ* speed for 22 events associated with eruptive flares. Their analysis was based on observations by the eight spacecraft (Explorer 33, 34, 35, 41, and 43; Pioneer 7 and 8; and Ogo 5). The in situ speeds were lower than the mean transit speeds, suggesting that shocks decelerated.

Mihalov *et al.* (1987) compared the transit speed of shocks from the Sun to the Pioneer Venus Orbiter (PVO) spacecraft with the transit speed from the Sun to Earth. The transit speeds to Earth tended to be less than those to Venus, indicating deceleration of the shock during propagation. The faster shocks tended to have greater deceleration.

Cane (1983) deduced the velocity profiles of shocks from interplanetary (IP) type II observations by the ISEE 3 spacecraft. The shocks accelerated near the Sun, then decelerated.

Volkmer and Neubauer (1985) analyzed 178 fast magnetohydrodynamic (MHD) shocks observed by the HELIOS-1 and -2 spacecraft. They found that speeds in the solar wind frame are roughly proportional to $R^{-0.5}$, where R is the distance in astronomical units (AUs).

Smart and Shea (1985) constructed a simplified shock propagation model based on Volkmer and Neubauer's (1985) finding. They assumed that a shock is initially driven near the Sun, then changes into a blast wave as it propagates through the interplanetary medium. Pinter and Dryer (1990) extended their study by considering solar radio emission in association with the eruptive flares to determine the initial driven condition of the shock. Their extended model showed good agreement for 39 shock events between 1972 and 1982.

Cliver *et al.* (1990) examined the relationship between transit shock speed Vt and the corresponding maximum solar wind speed at Earth, $Vmax$. They obtained $Vmax = 0.775 \cdot Vt$ - 40 km/s.

Vlasov (1988) analyzed the interplanetary scintillation observations and noted that the shock speeds, including the background solar wind, are proportional to $R^{-\gamma}$, where $0.25 \leq \gamma \leq 1$. Beyond 2 AU, Dryer *et al.* (1978) noted that the transit shock speeds are proportional to $R^{-0.08}$.

Theoretical approaches to shock propagation have been intensively investigated since Parker's pioneering work (Parker, 1963). Reviews of this work include Dryer (1974, 1994), Hundhausen (1985, 1988), Pizzo (1985), and Dryer *et al.* (1988).

Smith and Dryer (1990) used $2\frac{1}{2}$-dimensional magnetohydrodynamic ($2\frac{1}{2}$-D MHD) time-dependent simulation for a parametric study of interplanetary shock propagation. They summarized the expected properties of the shocks at 1 AU for several levels of energy input near the Sun.

We have statistically analyzed the in situ shock observations and found a useful index for estimating the transit speed. We compared our results with those of Smith and Dryer's (1990) MHD simulation and with those of a simple model assuming a blast wave. We identified several shocks that appear to have accelerated even in the slow-speed solar wind.

2 Statistical analysis of local and transit shock speeds

2.1 Observed deceleration at 1 AU

Cane *et al.* (1987) listed the relation among interplanetary shocks, IP type II radio bursts, and coronal mass ejections (CMEs). We used their result to determine the relation between transit and in situ local speed so that we could estimate the shock deceleration at 1 AU.

Cliver *et al.* (1990) found that Vmax, the peak speed of a transit disturbance, equals $0.775 \cdot Vt - 40$ km/s for average shock speed Vt. Their result is based on Cane's (1985) list, which describes the relation between flares and IP type II shocks. Cane *et al.* (1987) re-examined Cane's (1985) list by using the coronagraph images

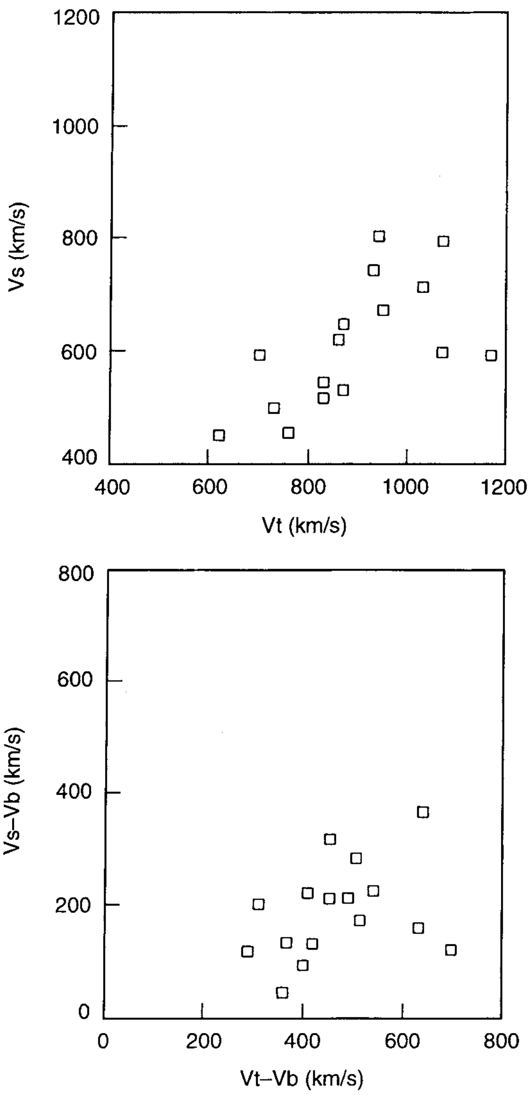

Fig. 1. Scatter plots of Vs versus Vt (*upper panel*) and ($Vs - Vb$) versus ($Vt - Vb$) (*lower panel*)

Table 1. Sixteen interplanetary shocks selected from Cane *et al.* (1987)

CME		SC		Vt (km/s)	Vs (km/s)	Vb (km/s)	Vs/Vt	$(Vs - Vb)/(Vt - Vb)$
Date	Time (UT)	Date	Time (UT)					
1979.04.03	0252	04.05	0155	860	622	408	0.79	0.47
1979.08.18	1639	08.20	0625	1030	717	489	0.70	0.42
1979.08.26	2016	08.29	0459	700	594	390	0.85	0.66
1980.04.04	1541	04.06	1059	950	675	460	0.71	0.44
1981.04.01	0222	04.03	0347	830	517	472	0.62	0.13
1981.05.08	2335	05.10	2208	870	531	356	0.61	0.34
1981.05.13	0415	05.14	1856	1070	600	438	0.56	0.26
1981.05.14	0900	05.16	0532	930	746	522	0.80	0.55
1981.05.16	1042	05.17	2302	1070	799	430	0.75	0.58
1981.08.07	2003	08.10	0434	730	499	364	0.68	0.37
1981.11.09	1350	11.11	1238	870	650	364	0.75	0.57
1981.11.22	0759	11.25	0229	620	450	331	0.73	0.41
1981.12.09	2051	12.12	0144	760	455	361	0.60	0.24
1981.12.27	0327	12.29	0455	830	545	412	0.66	0.32
1982.01.30	0100	02.01	1100	1170	595	472	0.51	0.18
1982.09.04	0324	09.05	2250	940	807	487	0.86	0.71
Average ± SD				889 ± 144	613 ± 110	422 ± 56	0.70 ± 0.10	0.42 ± 0.16

Table 2. Forty four interplanetary shocks observed by the HELIOS-1 spacecraft based on Sheeley *et al.* (1985)

CME		Shock		Location (AU)	Vt (km/s)	Vs (km/s)	Vb (km/s)	Vs/Vt	$(Vs-Vb)/(Vt-Vb)$
Date	Time (UT)	Date	Time (UT)						
1979.06.09	1613	06.11	2055	0.60	480	325	267	0.68	0.27
1979.07.19	1010	07.21	1820	0.93	740	460	326	0.62	0.32
1979.10.10	0713	10.13	0200	0.72	475	440	308	0.93	0.79
1979.12.13	0945	12.15	1236	0.55	460	380	297	0.83	0.51
1980.02.27	0431	02.29	1455	0.98	690	580	390	0.84	0.63
1980.03.02	2229	03.05	0145	0.98	750	525	367	0.70	0.41
1980.03.19	0706	03.22	1403	0.92	490	435	354	0.89	0.60
1980.03.27	1358	03.29	1153	0.89	770	640	355	0.83	0.69
1980.05.21	2143	05.22	2050	0.34	590	440	305	0.75	0.47
1980.06.02	0922	06.03	0914	0.33	570	390	257	0.68	0.42
1980.06.18	0757	06.19	1930	0.53	620	530	277	0.97	0.74
1980.06.20	1530	06.22	2000	0.57	430	415	292	0.97	0.89
1980.07.09	0158	07.10	2238	0.76	680	550	384	0.81	0.56
1980.07.18	0842	07.20	2300	0.84	545	465	330	0.85	0.63
1980.07.29	1331	08.01	1013	0.91	550	495	388	0.90	0.66
1980.09.01	0735	09.03	1206	0.98	770	590	326	0.77	0.68
1980.11.14	0820	11.14	2136	0.51	1510	1305	486	0.86	0.80
1980.11.17	1123	11.18	1345	0.46	665	565	446	0.85	0.54
1981.01.25	1104	01.27	0001	0.84	890	705	450	0.81	0.58
1981.01.26	0313	01.27	1745	0.84	875	700	450	0.80	0.59
1981.02.26	2030	03.01	0110	0.98	760	655	400	0.86	0.71
1981.03.06	2053	03.09	2100	0.98	550	445	300	0.81	0.58
1981.03.19	0120	03.21	0700	0.97	745	660	360	0.89	0.78
1981.04.01	0222	04.03	0547	0.94	740	510	350	0.69	0.41
1981.04.06	0909	04.08	0246	0.92	905	730	400	0.81	0.65
1981.04.10	1136	04.13	0906	0.89	520	435	300	0.84	0.61
1981.04.18	0148	04.20	0100	0.85	740	530	350	0.72	0.46
1981.05.08	2335	05.10	0320	0.67	970	650	480	0.67	0.35
1981.05.10	1239	05.11	0710	0.66	1440	1330	600	0.92	0.87
1981.05.13	0415	05.13	2120	0.63	1470	1310	600	0.89	0.82
1981.05.16	1042	05.16	2200	0.59	1790	605	300	0.34	0.20
1981.07.20	1913	07.21	2336	0.72	870	735	310	0.84	0.76
1981.07.22	2049	07.24	1528	0.74	710	635	450	0.89	0.71
1981.08.15	2118	08.18	1528	0.92	570	540	400	0.95	0.82
1981.10.18	0336	10.20	1358	0.89	620	555	300	0.90	0.80
1981.11.15	0015	11.16	1519	0.67	680	545	320	0.80	0.63
1982.01.10	0606	01.12	0654	0.54	455	405	310	0.89	0.66
1982.02.10	0457	02.11	1119	0.84	1020	765	690	0.75	0.23
1982.02.23	2237	02.27	0158	0.93	500	435	400	0.87	0.35
1982.06.03	1203	06.04	1026	0.55	1005	840	350	0.84	0.75
1982.06.05	1638	06.06	1603	0.52	905	750	490	0.83	0.63
1982.07.12	1203	07.13	0302	0.44	1030	930	550	0.90	0.79
1982.07.22	1720	07.23	0830	0.56	1505	1200	420	0.80	0.72
Average $\pm$ SD				0.74 ± 0.19	792 ± 319	631 ± 247	383 ± 96	0.81 ± 0.11	0.61 ± 0.18

taken by the Solwind spacecraft in association with IP type II shocks. Then they made the IP type II event list associated with CMEs. Cliver *et al.* (1990) used maximum bulk flow velocity $Vmax$ instead of local shock speed Vs. They did not consider the background solar speed Vb in their analysis.

We checked the availability of solar wind data for the shocks in Canes's (1987) list and selected sixteen shocks. We added Vs, Vb, Vs/Vt, and $(Vs-Vb)/(Vt-Vb)$ by using the OMNI data. Table 1 shows the sixteen shocks.

The average ratio of Vs/Vt is 0.70 ± 0.10. This ratio is 0.42 ± 0.16 after subtracting background solar wind speed Vb from both Vs and Vt. Here we consider the slow solar wind preceding the shocks as the background solar wind speed Vb. The expected ratio $(Vs-Vb)/(Vt-Vb)$ for the blast wave is 0.5. The scatter plots of Vs versus. Vt and $(Vs-Vb)$ versus $(Vt-Vb)$ are shown in Fig. 1.

2.2 Distance dependence

To analyze the distance dependence of the ratio Vs/Vt, we selected 44 interplanetary shocks observed in association with CMEs and where the ratio Vs/Vt is less than one. Table 2 shows these shocks. These shocks were observed by the HELIOS-1 spacecraft (Sheeley *et al.*, 1985). The HELIOS-1 spacecraft observed the solar wind at various solar distances.

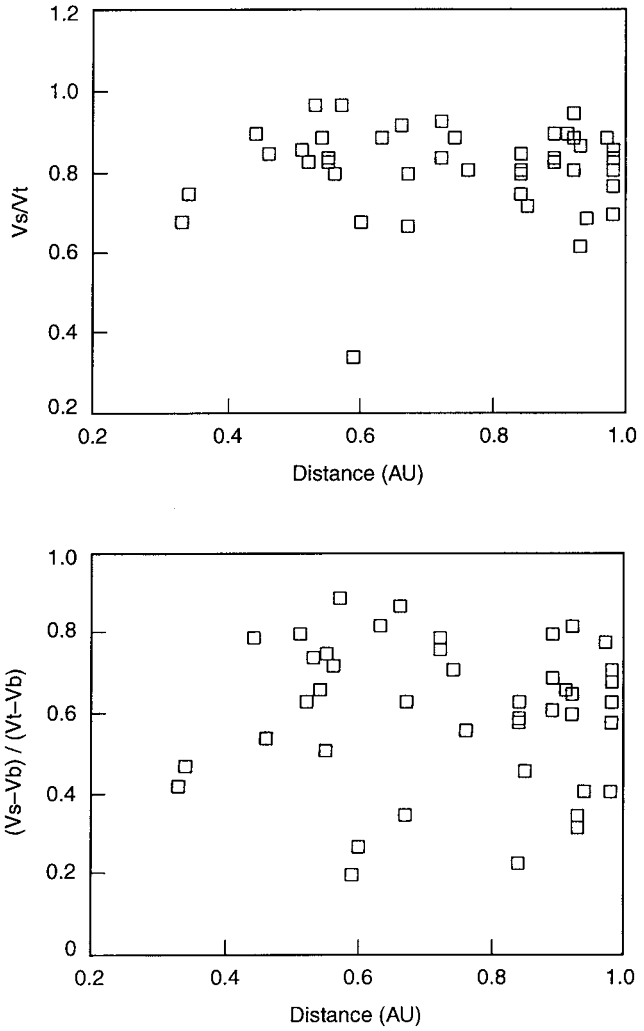

Fig. 2. Local-shock-speed dependence of the Vs/Vt (*upper panel*) and $(Vs - Vb)/(Vt - Vb)$ (*lower panel*).

Table 3. Distance dependence of ratios between transit and local shock speeds

Distance (AU)	Number of data	Vs/Vt	$(Vs - Vb)/(Vt - Vb)$
0.25–0.50	4	0.80 ± 0.09	0.56 ± 0.14
0.50–0.75	17	0.82 ± 0.15	0.65 ± 0.20
0.75–1.00	22	0.81 ± 0.08	0.58 ± 0.15

Figure 2 shows the distance dependence of the ratios Vs/Vt and $(Vs - Vb)/(Vt - Vb)$. The distance dependence of both is weak. This suggests that the shock speeds were decelerated according to the same radial dependence in this range.

The scatter of the data increases after subtracting the background solar wind speed. The average ratios in $0.25 - 0.50$, $0.50 - 0.75$, and $0.75 - 1.00$ AU ranges are summarized in Table 3.

2.3 Comparison with MHD simulation

Smith and Dryer (1990) calculated the shock propagation from the Sun to Earth under several initial conditions by using MHD simulation. They put shock pulses at 1.8 Rs (solar radius) into their computational domain. The steady-state background solar wind was assumed. It was taken to be uniform in azimuth in ecliptic plane, and the interplanetary magnetic field had the form of an Archimedian spiral. The ratios based on their result (Fig. 7 in Smith and Dryer, 1990) are summarized in Table 4. Vi is initial shock speed. The ratios between the average transit speed and the local speed vary between 0.70 and 0.83. Those ratios are between 0.47 and 0.80 after the background solar wind speed was subtracted. The effect of the background solar wind becomes weak for strong shocks with a long driving time.

Smith *et al.* (1995) calculated the Vs/Vt for the flux rope propagation obtained by MHD simulation to be $0.7 \sim 0.9$, which is in line with our result.

3 A simplified shock propagation model

We examined the observational results by using the simplified model of Smart and Shea (1985).

We assumed the following radial distance dependence of shock speed V_S, where R is the radial distance ($R_1 < R_2$), and that background solar wind speed V_0 is constant.

$$\left.\begin{array}{ll} V_S = V_{S0} + V_0 & \text{for } R \le R_1 \\ V_S = V_{S0}(R/R_1)^{-\alpha} + V_0 & \text{for } R_1 \le R \le R_2 \end{array}\right\} \quad (1)$$

Transit time T_{R2} to R_2 is given by

$$T_{R2} \simeq \frac{\alpha}{1+\alpha}\frac{R_1}{V_{R1}} - \frac{\alpha}{(1+\alpha)(1+2\alpha)}\frac{V_0 R_1}{V_{R1}^2} + \frac{1}{1+\alpha}\frac{R_2}{V_{R2}} + \frac{\alpha}{(1+\alpha)(1+2\alpha)}\frac{V_0 R_2}{V_{R2}^2} \ , \quad (2)$$

Table 4. Interplanetary shock speeds deduced from MHD simulation by Smith and Dryer (1990)

Vi (km/s)	τ (h)	Vt (km/s)	Vs (km/s)	Vb (km/s)	Vs/Vt	$(Vs - Vb)/(Vt - Vb)$
1000	0.5	700	520	360	0.74	0.47
1000	2	800	610	360	0.76	0.57
2000	0.5	1360	950	360	0.70	0.59
2000	2	1700	1400	360	0.82	0.78
3000	0.5	2100	1500	360	0.71	0.66
3000	2	2600	2150	360	0.83	0.80

where

$$\left.\begin{array}{ll} V_{R1} = V_{S0} + V_0 & \text{at } R_1 \\ V_{R2} = V_{S0}(R_2/R_1)^{-\alpha} + V_0 & \text{at} R_2 \end{array}\right\} \tag{3}$$

The ratio between local shock speed V_{R2} and transit speed $\langle V_{R2} \rangle$ is

$$\frac{V_{R2}}{\langle V_{R2} \rangle} = \frac{V_{R2}}{R_2/T_{R2}} \simeq \frac{1}{1+\alpha}\left(1 + \alpha \frac{R_1}{R_2}\frac{V_{R2}}{V_{R1}}\right) + \frac{\alpha}{(1+\alpha)(1+2\alpha)}\left(\frac{V_0}{V_{R2}} - \frac{R_1}{R_2}\frac{V_0 V_{R2}}{V_{R1}^2}\right) \tag{4}$$

If $\alpha = 0.5$ (Volkmer and Neubauer, 1985), then

$$\frac{V_{R2}}{\langle V_{R2} \rangle} \simeq \frac{2}{6}\left(2 + \frac{R_1}{R_2}\frac{V_{R2}}{V_{R1}}\right) + \frac{1}{6}\left(\frac{V_0}{V_{R2}} - \frac{R_1}{R_2}\frac{V_0 V_{R2}}{V_{R1}^2}\right) \tag{5}$$

Here $R_1 < R_2$ and $V_0 < V_{R2} < V_{R1}$.

If $R_1 \approx 0$, then $\frac{V_{R2}}{\langle V_{R2} \rangle} \approx \frac{2}{3} + \frac{1}{6}\frac{V_0}{V_{R2}} < \frac{5}{6}$.

According to these considerations, the ratio of the local speed to the transit speed is between 2/3 and 5/6. It is a function of the deceleration rate, the local speeds, and the background solar wind speed.

4 Acceleration of shocks

Table 5 shows seven shocks where the ratio Vs/Vt is more than one in Sheeley *et al.*'s (1985) list. The ratio of more than one means acceleration occurs during propagation. There is a possibility that this accelerations might result from a mis-identification of the associated CME. However, Woo *et al.* (1984) and Richter *et al.* (1985) noted a slight acceleration of the shock in the spacecraft radio scintillation measurements and in situ Helios solar wind observations for the shock on July 3 1979 in Table 5. The average Vs/Vt is 1.14 ± 0.12 for the seven shocks.

The quiet solar wind speed, Vq, at R astronomical units is given by $Vq \sim 2V_*(\ln\frac{R}{R_*})^{1/2}$, where $R_* = \mathrm{GMm}/4\mathrm{kT}$, $V_* = 2\mathrm{kT/m}$, M is the mass of the Sun, G is the universal gravitational constant, k is the Boltzmann constant, m is the sum of the proton and electron masses, and T is the temperature.

The ratio of local speed Vq and transit speed Vqt of the quiet solar wind is

$$Vq/Vqt \sim 1 + \frac{1}{2}(\ln\frac{R}{R_*})^{-1} + \frac{3}{4}(\ln\frac{R}{R_*})^{-2} + \frac{15}{8}(\ln\frac{R}{R_*})^{-3} \tag{6}$$

$Vq/Vqt \sim 1.2$ for $R_* \ll R$.

This ratio is similar to the observed ratio for a continuously accelerating shock. This suggests possible interaction between the shock and the background solar wind.

5 Concluding remarks

We have developed an index that is useful for estimating the transit speed of interplanetary shocks by statistically analyzing in situ observations. The index is the ratio between the local speed and the transit speed and is between 0.6 and 0.9 for most observed shocks. It is between 0.3 and 0.7 after subtracting background solar wind speed. The radial distance dependence of this ratio is weak.

We applied a simplified shock propagation model and showed that it can explain the observational results. However, the ratio is affected by several factors: deceleration ratio α, local shock speed V_S, background solar wind speed V_0, and so on. Calculation of the index for the MHD simulation results by Smith and Dryer (1990) showed good agreement with our results.

For the several shocks in Sheeley *et al.*'s (1985) list, the ratio is approximately 1.2. This suggests that these shocks were continuously accelerating while they transited from the Sun to Earth. This ratio of 1.2 is similar to the ratio calculated for the background solar wind acceleration. Gosling and Riley (1996) used the MHD simulation to show that slow CMEs accelerate in high-speed solar wind. Their analysis based on the CMEs identified in the Ulysses data (Gosling *et al.*, 1994, 1995). Here we show the existence of continuously accelerating shocks even in slow-speed solar wind.

Associations between solar events and SC storms have been often made regardless of solar wind data. The relationship between transit speed and in situ shock speed discussed here and the relationship between bulk speed of solar wind and transit speed developed by Cliver *et al.* (1990) have the ability to verify associations

Table 5. Examples of continuously accelerating interplanetary shocks

CME		Shock		Location (AU)	Vt (km/s)	Vs (km/s)	Vb (km/s)	Vs/Vt	$(Vs - Vb)/(Vt - Vb)$
Date	Time (UT)	Date	Time (UT)						
1979.05.27	1044	05.28	1840	0.43	560	605	354	1.08	1.22
1979.07.03	0156	07.05	1100	0.83	610	655	396	1.07	1.21
1981.04.10	2112	04.13	0957	0.89	570	770	300	1.35	1.74
1981.11.18	2111	11.20	0047	0.63	910	1170	310	1.29	1.43
1981.11.19	0300	11.20	1234	0.63	790	985	400	1.25	1.50
1982.07.19	0223	07.20	0551	0.53	770	825	400	1.07	1.15
1982.07.19	0942	07.20	0919	0.53	890	925	480	1.04	1.09
Average ± SD				0.64 ± 0.15	729 ± 137	848 ± 182	377 ± 57	1.14 ± 0.12	1.28 ± 0.21

between solar and interplanetary events. Use of these relationships can add confidence to solar event/SC storm associations.

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